Fully-coupled Hydrologic Processes for Modeling Landscape Evolution

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ABSTRACT

Investigating the impacts of properties, distribution and evolution of regolith on river channel, fluid pathways, flow rate and sediment transport is essential to resource management and restoration efforts. Under relatively constant forcing, current landscape evolution models predict landscapes with specific concave-convex slopes, spatially variable regolith thicknesses, drainage densities and relief. But these models do not include realistic groundwater and overland flows, bedrock weathering, and channel-hillslope interactions. This study fully couples the hydrologic processes in the Penn State Integrated Hydrologic Model (PIHM) with hillslope and channel sediment transport processes to form a 3D hydrologic-morphodynamic model (LE-PIHM) for regolith formation and landscape evolution.

LE-PIHM computes the feedbacks among infiltration, recharge, groundwater and surface water runoff, creation of regolith and its erosion by streams, and downslope movement by tree-throw by using the semi-discrete finite volume strategy. Two scenarios are presented here to demonstrate the importance of this coupling: 1) simulation of landscape evolution without groundwater flow, and 2) simulation of landscape evolution fully coupled with groundwater flow. The comparison of the landforms at steady state indicates that the hill slope is steeper in the simulation with groundwater flow than the simulation without groundwater flow. Three non-dimensional parameters govern the behavior of the system: 1) W*=Po/U, the ratio of the weathering rate of bare bedrock to the rock uplift rate; 2) K*=K/UL, the ratio of hillslope diffusivity to rock uplift rate times a system lengthscale; and 3) S*=D/UL, the ratio of overland sediment transport diffusivity to uplift rate times a system lengthscale. Steady-state landforms of an artificial watershed possess convex and smooth channel profiles if K* relative large and S* is small, whereas S* dominant landscapes possess concave and sharp channel and mountain profiles. The set of analysis also reveal that even though the ratios are the same, higher uplift rate accelerates the time to steady state.

1. Model development

The landscape evolution model (LE-PIHM), fully coupled into The Penn State Integrated Hydrologic Model (PIHM), not only simulates the processes of weathering, bedrock uplift and regolith transport, but also computes the change of surface water, unsaturated water and saturated water due to the change of landform caused by the morphological processes. The same as PIHM does, this model uses semi-discrete finite volume approach quantitatively characterizing the time rate of change of ground elevation (h+e), regolith (h) and bedrock thickness (e).

Governing equations for rock and regolith

1.Evolution of ground surface

$$\frac{\partial z}{\partial t} = \left(\frac{\sigma_{ro}}{\sigma_{re}} - 1\right)\sec\theta P_0 e^{-\alpha H} - \frac{\partial q_x}{\partial x} + U - E$$

2. Evolution of bedrock

$$\frac{\partial e}{\partial t} = -\sec\theta P_0 e^{-\alpha H} + U$$

3. Evolution of regolith

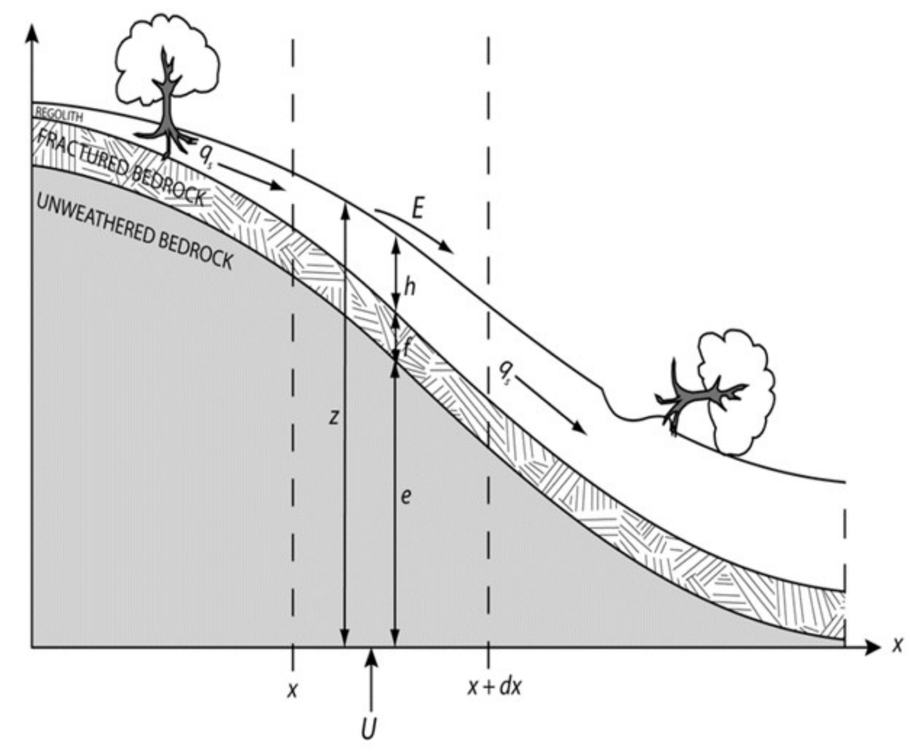
$$\frac{\partial h}{\partial t} = \frac{\partial z}{\partial t} - \frac{\partial e}{\partial t} = \frac{\sigma_{ro}}{\sigma_{re}}\sec\theta P_0 e^{-\alpha H} - \frac{\partial q_x}{\partial x} - E$$

4. General equation for downslope regolith flux due to tree throw

$$q_x = K_1\tan\theta + K_2\sin\theta\cos\theta + K_3\sin\theta$$

5. Downslope sediment transport

$$E = 4(\tau_0^* - \tau_c^*)^{\frac{3}{2}}\sqrt{RgD}D$$



Governing equations for hydrology

1. Overland flow

$$\frac{dQ_w}{dt} = A\frac{1}{n}\left(\frac{A}{P}\right)^{\frac{2}{3}} S^{\frac{1}{2}}$$

2. Unsaturated Flow

$$C(\Psi)\frac{\partial\psi}{\partial t} = \nabla\cdot(K_w(\Psi)\nabla(\Psi + z))$$

3. Groundwater Flow

$$C(\Psi)\frac{\partial\psi}{\partial t} = \nabla\cdot(K_w(\Psi)\nabla(\Psi + z))$$

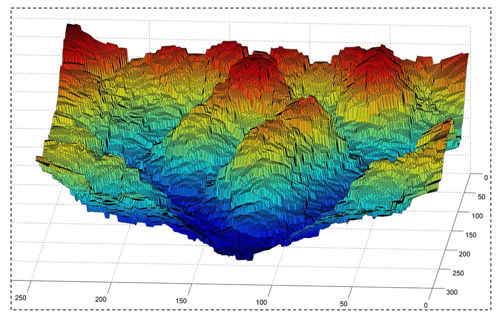
Parameters	Description	Unit
P_0	bare bedrock weathering	m/yr
K	Diffusivity of regolith flux	m^2/yr
τ^*_c	Critical shield stress	dimension
τ^*_0	Actual shield stress	dimension
D	Grain diameter	m
P	Wet perimeter	m
S	Gradient of Elevation	dimensionless
ψ	Matric potential	Pa
σ_{ro}	Rock density	Kg/m^3
σ_{re}	Rock density	Kg/m^3
θ	Slope	Degree
R	Submerged specific gravity	dimensionless

2. Model testing and examples

A. Non-dimensional analysis

There are three non-dimensional parameters representing the hydrologic and morphodynamic processes, $P^* = P_0/U$, $K^* = K/LU$, and $S^* = \beta/LU$.

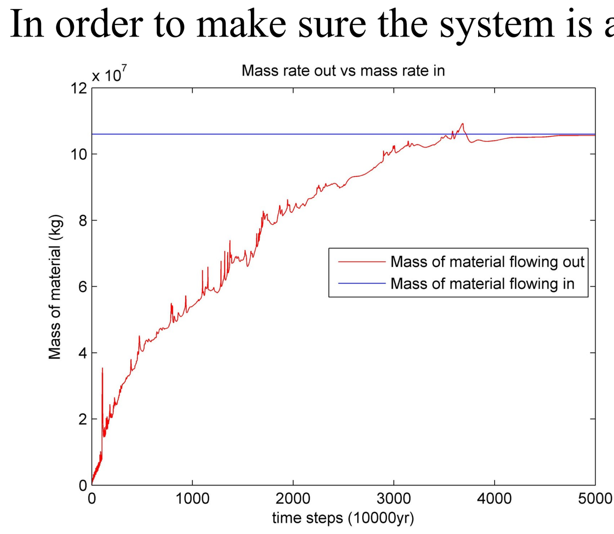
$$\frac{\partial z^*}{\partial t^*} = \frac{P_0}{U}\left(\frac{\sigma_{ro}}{\sigma_{re}} - 1\right)\sec\theta e^{-\frac{\alpha^*}{L}LH^*} - \frac{K}{LU}\frac{\partial^2(z^*)}{\partial(x^*)^2} - \frac{\sqrt{RgDD}}{LU}\frac{\partial(q_s^*)}{\partial x^*} + U^*$$



Here, we make P_0, L, and U constant and try to explore the landscape behavior governed by different combination of K^* and

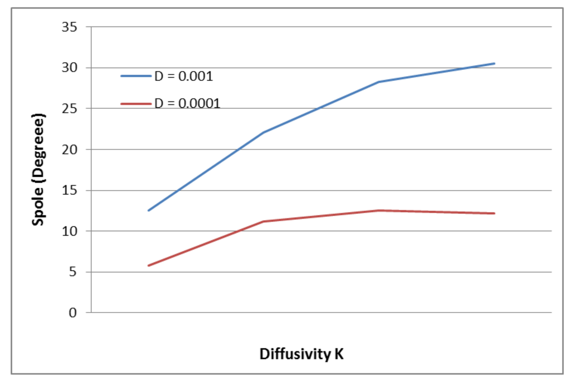
B. Comparison of landform at steady state based on different parameters

In order to make sure the system is at steady state, we checked the mass balance of regolith (mass rate in vs mass rate out).

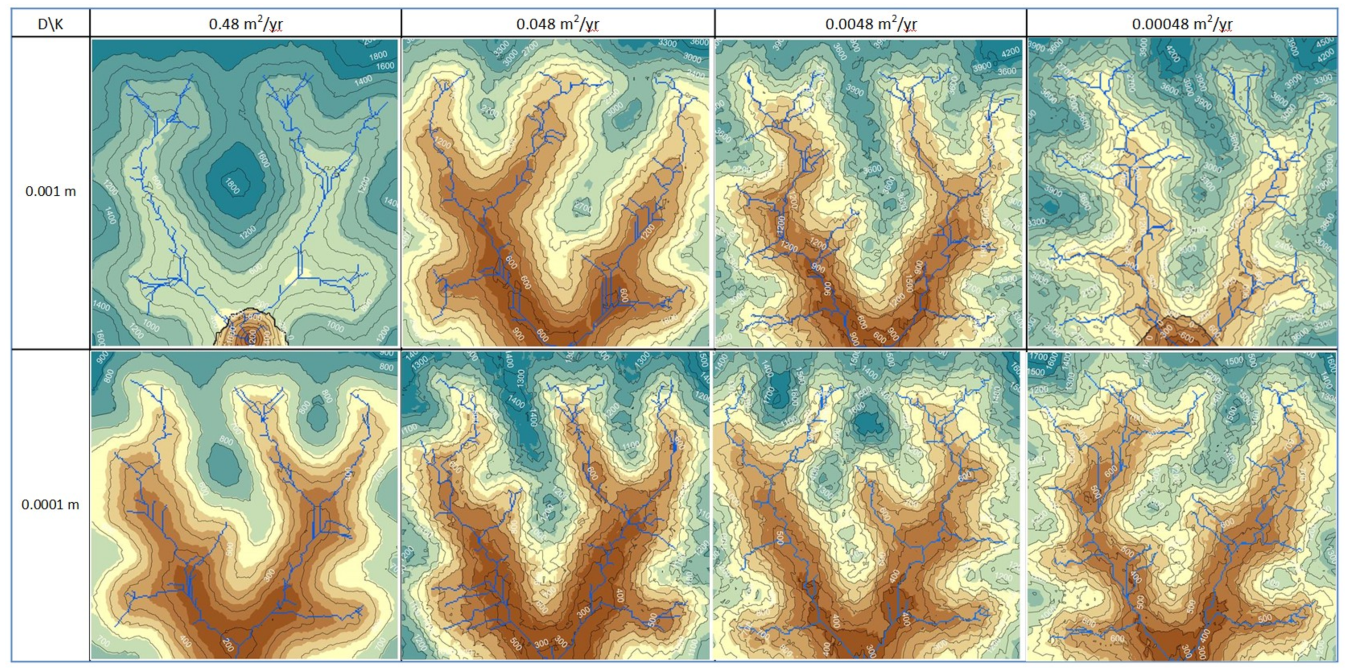


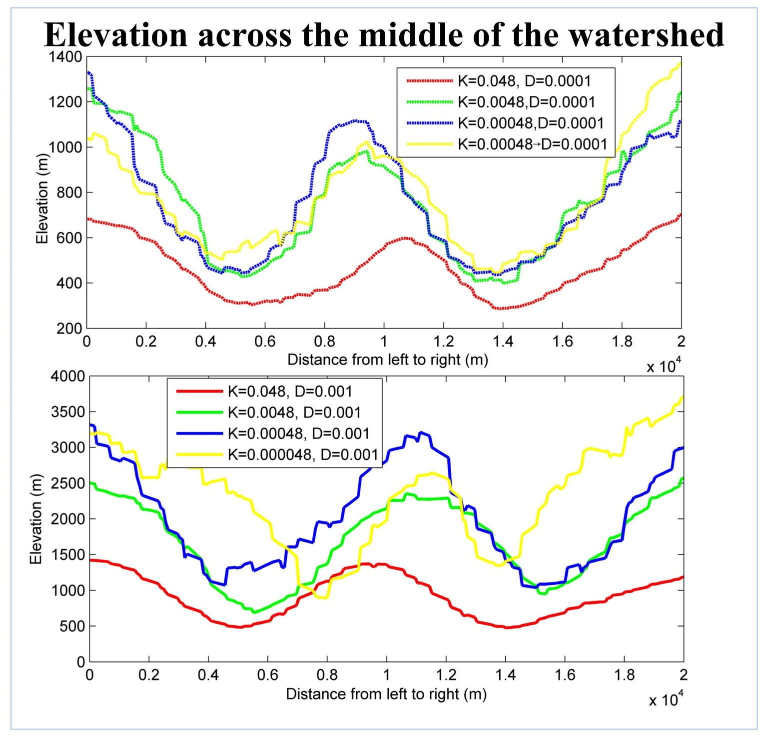
The mean slope of the 8 landforms at steady state

D\K	0.48 m^2/yr	0.048 m^2/yr	0.0048 m^2/yr	0.00048 m^2/yr
0.001 m	12.4942°	22.0709°	28.2794°	30.5288°
0.0001 m	5.7466°	11.1402°	12.5367°	12.1453°



Landscape evolution at steady state under different K (diffusivity) and D (grain size).





Left:

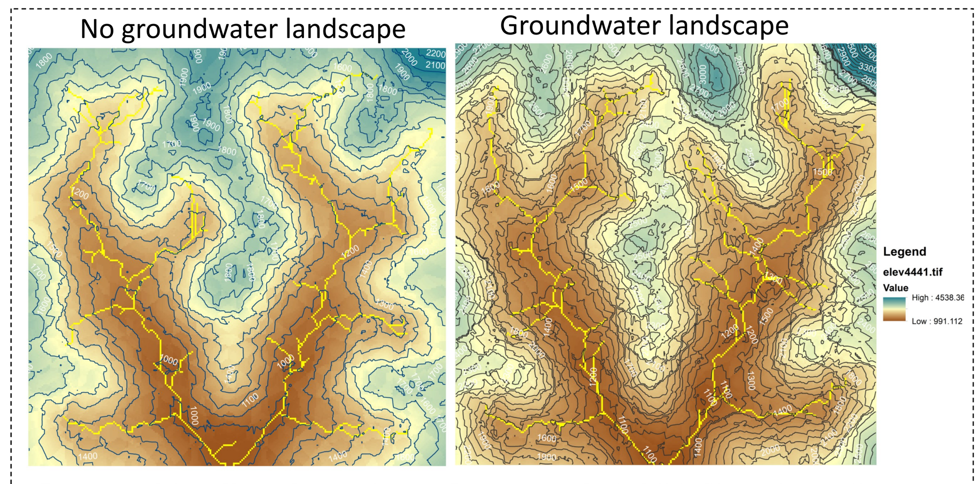
—Increasingly diffuse landscapes possess lower slopes and smoother contours

—Coarser grain sizes in the regolith create steeper slopes

—The highest elevation comes from the blue line

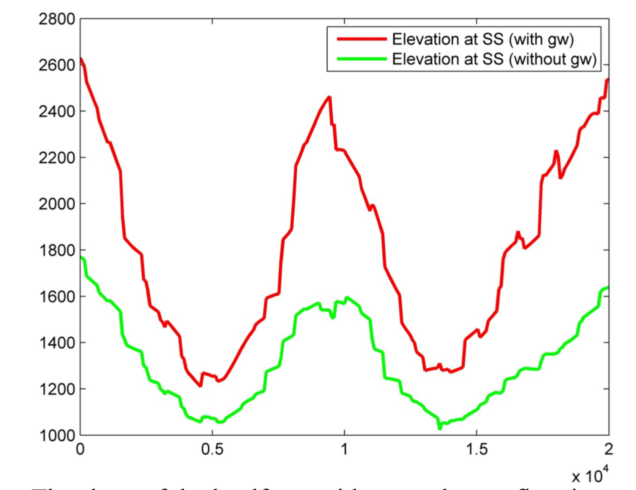
C. Landscape evolution with and without groundwater process

The initial ground surface is a flat landform with uniform constant rainfall and uplift rate. In this case, the diffusivity K = 0.0048 m^2/yr; the diameter of grain D = 0.001 m

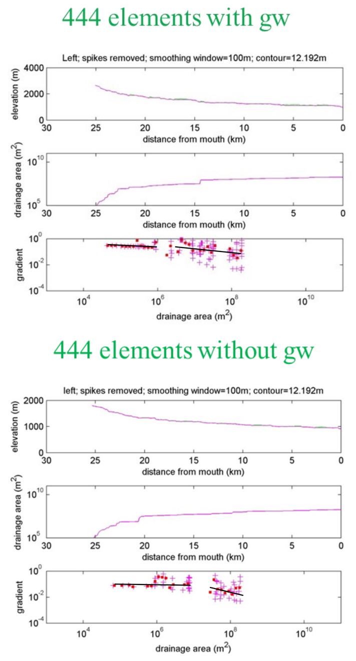


—Because of the effect of groundwater flow, parts of rainfall infiltrate into soil zone.

—The sediment transport rate is lower than the rate without groundwater flow due to the change of surface runoff.



—The slope of the landform with groundwater flow is steeper than the slope of the landform without groundwater flow



Left:

—The longitudinal profile of the western stream in the groundwater simulation is less concave

— θ in the slope-area relationship S k_s $A^{-\theta}$ falls within the range of natural landscapes in both cases

3. Summary

A new landscape evolution model (LE-PIHM) is introduced. It is coupled with a hydrologic model which includes the water exchange among soil zone.

By showing the differences of the channel and drainage area, we can see that it is important to couple groundwater flow which has a significant influence on the evolution of landscape.

4. Future work

Apply LE-PIHM in Shale Hills watershed